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Mathematical models for operations management

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‘The slower but consistent tortoise causes less waste and is much more desirable than the speedy hare that races ahead and then stops occasionally to doze. The Toyota Production System can be realized only when all the workers become tortoises’

Taiichi Ohno (1988)

ABSTRACT

Purpose – The purpose of the doctoral thesis is to support and to facilitate the introduction of lean concepts, in the industry.

Design/methodology/approach – Starting from the operating techniques included in the lean toolbox, a comprehensive set of twelve mathematical models for operations management is developed. Since Lean Thinking encompasses the whole organization, the models cover several processes performed by an organization. In particular there are: (*i*) three models dealing with logistic issues, (*ii*) five models concerning manufacturing issues, and (*iii*) four models concerning Total Predictive Maintenance.

Findings – The models extend the capabilities of the classical lean tools by means of advanced mathematical techniques such as: fuzzy logic, multi criteria decision making, multivariate statistic and Markov processes.

Practical implications – To assure the possibility to adopt the models in real industrial situations, a great effort has been made to maintain all of them as simple and straightforward as possible. Furthermore, all of them have been designed to be easily implemented in industrial information systems, and have been validated by means of industrial applications of relevance.

Originality/value – The twelve models here presented provide practitioners with innovative operating tools, which integrate different techniques and overcomes most of the limits of the classical lean tools.

Keywords *Lean Thinking, Mathematical Models, Operations*

SOMMARIO

Scopo – Il presente lavoro si prefigge di supportare l’introduzione dei concetti della produzione snella in ambito industriale.

Metodologia/Approccio seguito – Prendendo come riferimento i classici strumenti lean, sono stati sviluppati dodici modelli matematici per la gestione e l’ottimizzazione dei processi produttivi. Tali modelli riguardano tutte le principali tematiche aziendali e in particolare: (*i*) tre modelli trattano problematiche di natura logistica, (*ii*) cinque modelli riguardano aspetti inerenti la pianificazione della produzione e (*iii*) quattro modelli riguardano aspetti legati alla manutenzione preventiva.

Risultati – I modelli presentati ampliano le potenzialità degli strumenti lean, integrandoli con avanzate tecniche matematiche quali: logica fuzzy, metodi multi attributo, statistica multivariata, e catene di Markov.

Implicazioni pratiche – Per assicurarne l’applicabilità a problematiche industriali, tutti i modelli sono stati pensati per essere facilmente implementabili nei principali sistemi informativi industriali. Inoltre, per testarne le potenzialità, sono stati tutti validati mediante significative applicazioni industriali.

Originalità/valore – I dodici modelli rappresentano un importante insieme di tecniche operative che, mediante l’integrazione di differenti approcci matematici, permettono di superare molti dei limiti dei classici strumenti lean.

Parole chiave *Produzione snella, Modelli matematici, Processi aziendali*

PREFACE

Lean Manufacturing is a managerial philosophy intended to enhance value to customers by continuously adding product and/or service features, and by constantly removing waste from all the manufacturing processes performed by an organization. This approach has taken origin from a set of operative techniques and has progressively moved away from a merely "shop floor focus", to embrace in a holistic way the whole organization. Indeed in the last years, managers have realized that manufacturing is only a small part of any business and whilst one is implementing lean concepts there, the rest of the business is not being challenged. Thus, Lean Thinking (or Lean Enterprise) was introduced by Womak and Jones in the mid 90's to extend the lean principles to a whole business and even to a whole supply chain, from the last tier suppliers to the end customers. In other words, the big picture is to look at the segments of the supply chain and try to manage them, not as the sum of separate parts, but as joined and interdependent elements of a global system.

In this sense, lean thinking encompasses all the different facets of an organization and tries to produce products that meet customers' needs and expectations in a better way, by lining up and coordinating the value creating process for a finished product, that is performed along the supply chain. To this aim, it is firstly necessary to analyze the *value stream*, being all the activities, both value-added and non-value added, which are performed to manufacture an item (from raw materials to finished goods). Subsequently, all the wasteful steps must be removed so that a leveled flow can be introduced within the remaining value-added processes.

To support value stream analysis and to facilitate the introduction of lean principles, several operating tools (generally referred as *lean toolbox*) can be used by practitioners. Since Lean Thinking deals with the whole organization, the lean toolkit comprises well known techniques (such as 5S, OEE, Value Stream Mapping, SMED, kaizen, Total Productive Maintenance, poka yoke devices, just-in-time, cellular design, etc), that encompass all the processes performed by an organization: design, manufacturing, maintenance, inbound and outbound logistic, supplier selections, and many others.

Objectives of the doctoral thesis

The doctoral thesis deals with the previously discussed issues, aiming to support practitioners in the introduction of lean concepts in the industry. To this aim, the basic set of the lean operating tools has been improved and extended by means of twelve mathematical models, purposely designed to support practitioners in tackling the problems that can typically arise in an industrial environment. In particular, the models extend the capabilities of the classical lean tools by means of advanced mathematical techniques such as: fuzzy logic, multi criteria decision making, multivariate statistic and Markov processes.

Structure of the thesis and overview of the mathematical models

As previously noted, the mathematical models here proposed aim to support and to enhance lean concepts, by extending the capabilities of the standard lean toolkit.

To provide the reader with a minimal conceptual background, the first chapter gives an overview of the Lean Manufacturing principles and pinpoints the main aspects of the techniques included in the lean toolkit. All the other chapters are devoted to present and discuss the twelve mathematical models that constitute the core of the doctoral thesis.

As Lean Thinking deals with the whole organization, also the presented models cover several processes performed by an organization. In particular there are: (*i*) three models dealing with logistic issues, (*ii*) five models concerning manufacturing issues, and (*iii*) four models concerning Total Predictive Maintenance.

Inbound Logistic Models

Inventory is probably the worst form of waste and must be progressively eliminated before one can successfully implement a Lean Manufacturing plan. To facilitate this process, three innovative models are presented.

A dynamic model for inventory control (chapter 2)

This model concerns the optimization of the internal inventories, and challenges the basic assumptions of the classical models for inventory management. Indeed, a dynamic procedure that permits one to manage inventory, when demand is not stationary, but follows a generic trend is presented.

Starting form the assumption that the stock's consumption can be modeled as a Markov process with a slow diffusion term, the model makes it possible to dynamically update the optimal reorder point, taking into account both the evolution of the mean and that of the variance of the demand.

A framework for a dynamic evaluation of the optimal reorder quantity is also provided.

Material Requirement Planning for Vendor Managed Inventory (chapter 3)

This model permits one to optimize the overall stock distributed along a supply chain, through the implementation of Vendor Managed Inventory. As known, to operate under this strategy, different tiers of the supply chain (*i.e.*, the supplier and the manufacturer) must integrate their production planning and control processes. Especially on the supplier's side this is not always possible, mainly because the traditional Material Requirement Planning (MRP) is not structured to fulfill the requirements of a Vendor Managed Inventory (VMI) strategy. To solve this criticality, an operating model that permits one to easily integrate the productive data of the manufacturer in the MRP of its suppliers is presented.

The model is based on a simple closed loop control system and minimizes the average stock that is needed to assure the respect of the minimum (s) and of the maximum (S) stock that can be held in the warehouse of the manufacturer.

A standard contract for VMI (chapter 4)

Starting form the results presented in chapter three, a comprehensive framework to develop a VMI strategy is presented. The framework is synthesized in the form of a contract and can be used as a guideline to define VMI without overlooking any technical details.

Although this framework is not properly a mathematical model, it has been included in the doctoral thesis for its practical relevance and also because it describes a procedure, supported by discrete event simulation, which can be used to plan, schedule and control production in VMI agreements.

Manufacturing Models

Although at first sight it can seem weird, not only over production is an important causes of waste, but it is even difficult to be spotted. Indeed, making more components than that required by the customer and/or anticipating their production results in an excessive work in process, which, in turn, increases the inventory level, creates waiting queues and makes processing lead time uncertain.
To avoid all these problems five models are presented.

A new Value Stream Mapping approach for complex production systems (chapter 5)

This model integrates VSM with other tools typical of the industrial engineering and permits one to implement a pull production system in a job shop facility. As known, VSM is one of the main lean tool used to identify and to remove waste from a manufacturing process. Unfortunately, if the manufacturing process is complex, VSM becomes cumbersome and cannot be straightly applied. To solve this weakness the basic idea is that to use the Temporized Bill of Material to identify the critical production path. Once the critical path has been defined, improvements are made considering its linkages with secondary paths, as additional constraints.

Uncertainty in Value Stream Mapping (chapter 6)

Starting from the results of chapter five, a further improvement of VSM is presented. In particular, two alternative approaches to include variability analysis in VSM are proposed. Notoriously, VSM gives a deterministic image of the process and neglects its variability. This is a strong limit because, especially within manufacturing processes, variability has a significant impact both on operating costs and time. To overcome this weakness, two approaches for variability analysis are proposed: the first one is based on statistic and on the application of the Central Limit Theorem, while the second one is based on fuzzy triangular numbers and on fuzzy algebra. A critical comparison of the two methods is also presented.

CONWIP card setting in a flow shop system with a batch production machine (chapter 7)

This model permits one to define the optimal number of kanban cards employed to control jobs release in a CONWIP system. In particular a card setting procedure for a flow-shop system characterized by a batch processing machine is considered. Two different static approaches to control production plants where the bottleneck coincides or not with the batch machine are presented. In both contexts, the model makes it possible to optimize the flow-shop performances by maximizing the throughput with the minimum work in process.

A measurement method for the assessment of routing flexibility (chapter 8)

Flexibility is one of the main characteristic of lean processes. The model presented in this chapter focuses on routing flexibility, which is the ability to manufacture a part type via several routes and/or to perform different operations on more than one machine. In particular, the model permits one to measure in a comprehensive way the degree of routing flexibility of a manufacturing process. The problem is approached in a progressive way, starting from an initial routing flexibility index, which is progressively extended in order to include more comprehensive and complex routing aspects such as: (*i*) the average efficiency, (*ii*) the covering range and (*iii*) the homogeneous distribution of the alternative routes among different items. A graphical procedure to represent in a three dimensional space the routing flexibility is also presented.

A fuzzy multi-criteria approach for critical path definition (chapter 9)

The ability to schedule and to control complex projects is an important element of lean enterprises. To this scope an innovative model that extends the capabilities of the traditional project scheduling approaches is presented. The main goal is to determine the critical path taking into account not only the expected duration of the tasks, but also additional risk criteria. To this aim, a Fuzzy Logic procedure is applied to evaluate several risk criteria which are finally aggregated by means of the TOPSIS multi attribute decision making technique.

Total Productive Maintenance models

The reliability of the equipment installed in the flow shop is vital to assure the capability to meet the customer's demand. Indeed a leveled and strained flow cannot be obtained, unless one stabilizes the reliability of machines and of equipment.

An important way to enhance machines reliability is Total Productive Maintenance (TPM), which is an integrated approach based on five maintenance strategies: (*i*) corrective maintenance, (*ii*) auto maintenance, (*iii*) preventive maintenance (*iv*) proactive maintenance and (*v*) maintenance prevention.

To support TPM, four mathematical models are presented.

MTBF prediction with multivariate analysis approach (chapter 10)

The availability of a consistent estimation of the Mean Time Between Failure is fundamental to develop a predictive maintenance approach. To this aim, a statistical model to estimate the MTBF of mechanical components, installed in a process plant and working under specific operating conditions is presented. The methodology requires the availability of a structured set of failure data, that are processed with a multivariate statistical approach based on: (*i*) cluster analysis, (*ii*) multivariate analysis of variance (MANOVA), and (*iii*) discriminant analysis. As a result, an analytical function that makes it possible to classify new entries with respect to the expected working conditions, is obtained.

ANP/RPN: multi-attribute evaluation of the risk priority number (chapter 11)

Failure Mode Effect and Criticality Analysis is a fundamental method to identify the root causes of failures and to enhance proactive maintenance.

The model presented in this chapter permits one to improve the standard FMECA procedure by including in the criticality assessment the impact of the correlations among the causes of failure. To this aim FMECA is integrated with the Analytic Network Process (ANP) and the criticality parameters (*i.e.*, Severity, Occurrence and Detectability) are split in sub-criteria and arranged in a hybrid (hierarchy/network) decision structure, which is used to compute the Risk Priority Number (*RPN*).

Overall Equipment Effectiveness of a manufacturing line (chapter 12)

Overall Equipment Effectiveness (OEE) is a well known metric to measure the performance of individual equipment, and was originally introduced by Nakajima as the key index to support TPM. However, when machines operate jointly in a manufacturing line, OEE alone is not sufficient to improve the performance of the system as a whole. To overcome this limitation, a new metric (OEEML) and a step by step procedure to asses the performance of a line is presented. In particular the method is capable to highlights the progressive degradation of the ideal cycle time, explaining it in terms of: (*i*) bottleneck inefficiency, (*ii*) quality rate and (*iii*) synchronization-transportation problems.

Statistical evaluation of the Overall Equipment Effectiveness (chapter 13)
Starting form the results presented in chapter twelve, a further improvement to the OEE is made. In particular, an approximated approach to evaluate the probability density function of the OEE is presented. As known, OEE is a performance indicator adopted to support Lean Manufacturing. However, being a deterministic index it is not capable to point out the real variability of manufacturing performances, which is one of the main causes of waste. To solve this weakness, this chapter introduces an innovative approach based on the Central Limit Theorem that makes it possible to derive the pdf of the OEE starting from the pdf of the determinants of waste. The approach allows one to evaluate the OEE in statistical terms and also to estimate the impacts of potential corrective actions in terms of efficiency (*i.e.*, increase of OEE's average) and efficacy (*i.e.*, reduction of OEE's variability.

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